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## USES OF LUNAR SULFUR

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### Abstract

Sulfur and sulfur compounds have a wide range of applications for their fluid, electrical, chemical and biochemical properties. Although low in abundance on the Moon (~0.1% in mare soils), sulfur is surface-correlated and relatively extractable. Co-production of sulfur during oxygen extraction from ilmenite-rich mare soils could yield sulfur in masses up to 10% of the mass of oxygen produced. Sulfur deserves serious consideration as a lunar resource.

### Introduction

Volatile constituents such as molecular oxygen, nitrogen, water and hydrocarbons are rare on the Moon. The absence of such molecules is one of the problems that confronts prolonged lunar exploration or permanent lunar bases. The light-weight compounds of the elements from H to O are vital for life, and many of these elements play important roles as fuels, solvents, and industrial chemicals in processes that have become the necessities of industrialized life on Earth. The scarcity of these elements on the Moon thus raises two barriers against easy expansion into space, one against the simple need to stay alive and the other against easy transplantation of earthbound industrial processes.

With imagination this assessment need not be so bleak. Living in space will require adaptation, but it also opens opportunities to reassess the ways in which we live and use available resources. Sulfur on the Moon may

well prove a satisfactory replacement for lighter volatile elements and their compounds in some applications. It may even open new possibilities and uses that surpass a mere duplication of what is already done on Earth.

Our present knowledge of lunar samples suggests that the best place to collect sulfur on the Moon is from mare soils and rocks. Although sulfur is not so abundant that it is available without effort, it does rank 11th in weight abundance among the elements in average lunar mare rocks. Gibson and Moore (1974) found that the high-Ti mare basalts, in particular, have high sulfur contents, in the range of 0.16% to 0.27% by weight. These authors also make the important point that lunar basalts actually have more sulfur than terrestrial basalts, which seldom have more than 0.15%.

Although terrestrial basalts are relatively low in dispersed sulfur content, this sulfur is extracted and concentrated by circulation of heated water. This process results in the remarkable sulfur-rich environments at mid-ocean spreading ridges, where base-metal sulfides are deposited in great abundance and "unearthly" sulfur-metabolizing organisms proliferate. Clearly we can not expect heated water to have concentrated sulfur on the Moon. The relatively high sulfur content of lunar mare basalt 12036, however, led Gibson et al. (1977) to speculate on the possibility of Fe-FeS segregation and enrichment in some mare magmas. Discovery of sulfur-rich ore bodies on the Moon would be a major find that could accelerate exploitation immensely but, until their existence is actually proven, it would be unwise to plan on their use.

Another possible means for natural concentration of lunar sulfur may be vapor transport and deposition; the abundance of sulfur in volatile coatings on lunar pyroclastic glass droplets strongly suggests that sulfur was involved as a propellant gas in fire-fountain types of eruptions (Butler and Meyer, 1976). However, the analyses of volatile coatings on glass droplets suggest that significant amounts of sulfur are lost rather than trapped on droplet surfaces as a result of pyroclastic eruption. For example, the sulfur contents of the famous pyroclastic "orange glass" deposit of Shorty Crater at Apollo 17 contains only 0.06-0.08% sulfur (Gibson and Moore, 1974), whereas comparable chilled Apollo 17 lavas retain more than 0.16% sulfur.

Unless geologic traps for volatile sulfur are found on the Moon (Perhaps in vesicle pipes or lava tubes?), there is reason to believe that lunar volcanic gasses have acted more effectively in the dispersal of sulfur than in its concentration. The formation of soil on top of sulfur-rich lava flows also results in relative sulfur loss, probably through the combined processes of sulfur volatilization by small meteoritic impacts and of dilution by addition of sulfur-poor highland materials. For practical purposes, the ranking of sulfur contents presently known in lunar samples is about as shown in Table 1.

Table 1

High-Ti mare basalts (A-17)	0.16-0.27% (av. 0.21%)
Low-Ti mare basalts (A-12)	0.06-0.15% (av. 0.11%)
High-Ti mare soils (A-17)	0.06-0.13% (av. 0.10%)
Low-Ti mare soils (A-15)	0.03-0.06% (av. 0.05%)
Highland rocks (A-16)	0.01-0.14% (av. 0.07%)
Highland soils (A-16)	0.03-0.09% (av. 0.06%)

Data from Gibson and Moore (1973, 1974), Gibson et al. (1977), Kerridge et al. (1975), and LSPET (1972). Note that the ranges and averages cited are for specific Apollo sites (12, 15, 16 and 17); the data include possible analytical differences between laboratories.

Although the richest known sources of sulfur are the high-Ti mare basalts, extraction of this sulfur would require energy-intensive crushing of hard rock. The easiest source of sulfur is high-Ti mare soils, which need not be crushed prior to extraction of the dominantly surface-correlated sulfur. The mineralogic form of this surface-correlated sulfur is poorly known; some may occur as metal sulfates that are readily volatilized to produce  $\text{SO}_2$  (D. McKay, personal communication, 1988). However, deposits of sulfides and even elemental sulfur can not be ruled out. The simple heating experiments of Gibson and Moore (1973) on Apollo 15 and 16 samples indicate that at 750°C 12-30% of the soil sulfur can be extracted, at 950°C 50-70% of the sulfur is extracted, and at 1100°C 85-95% of the sulfur is extracted (vacuum conditions,  $<2 \times 10^{-6}$  torr). Moreover, sulfur is not the only

volatile element to be won. Heating of high-Ti pyroclastic deposits to 1200°C will provide some co-generation of Zn (0.01-0.03%), Na, K, Cl (0.002-0.010%), F (0-0.02%), and other vapor-transported elements (Cirlin and Housley, 1979; Butler and Meyer, 1976, Meyer et al., 1975). Heating will also be useful in the co-generation of small amounts of hydrogen (about 0.001-0.020%), helium (0.001-0.006%), carbon (0.004-0.028%), and nitrogen (0.007-0.015%) that are surface-correlated in lunar soils (Williams and Jadwick, 1980).

Thus, although sulfur is not richly concentrated on the Moon, it is present in sufficient abundance and (on pyroclastic particles) associated with other potentially useful elements that make the mining of lunar sulfur worth serious consideration. However, this consideration will not go very far if there is not a well-established set of end uses for the sulfur and its co-deposited elements. Sulfur has a broad range of chemical and physical properties which may make it extremely useful. Perhaps most importantly, sulfur and sulfur compounds have the capacity to substitute for water in many aqueous-based mechanical and chemical processes on Earth. Sulfur research is so broad and diverse that we can not fully cover its terrestrial applications in this short paper. Moreover, we can only begin to speculate on the possible uses of sulfur in space. Our purpose is rather to suggest several starting points for more imaginative studies on the uses of lunar sulfur. These starting points are discussed below under three broad categories; (1) the use of sulfur fluid properties, (2) the use of sulfur electrical properties, and (3) the use of sulfur chemical and biochemical properties.

#### The use of Sulfur Fluid Properties

Pure sulfur is fluid over a broad range of temperatures. Depending on crystal form, sulfur melts at 112.8°C (orthorhombic) or 119.25°C (monoclinic). Although the liquid does not boil until 444.6°C, it begins to lose its low-temperature fluidity and become very viscous at about 160°C. Figure 1 shows the variability of viscosity with temperature. At lunar daytime temperatures (~107°C) minimal heat input would maintain sulfur as a low-viscosity liquid.

Contrasted with pure sulfur,  $\text{SO}_2$  has a more useful range of fluid properties and has physical-chemical properties that can fit special requirements. Sulfur dioxide is liquid between  $-75.52^\circ\text{C}$  and  $-10.08^\circ\text{C}$ , with corresponding viscosities between 0.0068 and 0.0043 poise. This liquid is a polar solvent, although its dipolar attractive field is weaker than that of water. Where water is an excellent solvent for strong dipoles, liquid  $\text{SO}_2$  is a better solvent for nonpolar or easily polarized molecules. Sulfur dioxide is a good solvent for halogens and for olefinic and aromatic hydrocarbons, but is a poor solvent for aliphatic hydrocarbons (Burow, 1970). The halogens are quite soluble in liquid  $\text{SO}_2$ ; metal chlorides are highly soluble and this property may be particularly important on the Moon. There is strong evidence that many of the metals (e.g. Zn and Ga) with high boiling points that are found on the surfaces of lunar pyroclastic particles were transported and deposited as more volatile metal chlorides (Meyer et al., 1975). If this is the case, then these deposits might be easily stripped and collected from pyroclastic deposits using an  $\text{SO}_2$  washing process.

There are many potential uses of  $\text{SO}_2$  as a fluid. Some attractive possibilities are in refrigerant systems, in turbines (Rankine cycle), in heat transfer systems (liquid phase), in heat pipes (gas phase), in slurry lines for regolith or waste transport, and in hydraulic systems. Availability of  $\text{SO}_2$  will open a broad range of possibilities for controlling energy and materials on the Moon.

#### The Use of Sulfur Electrical Properties

Sulfur, especially in Na-S combinations, has potential use in both solar energy collection systems and in storage batteries.

#### Solar Energy Conversion

There is considerable active research into  $\text{Cu}_2\text{S}$ -based thin film solar cells and several sulfur-bearing photoelectrochemical (PEC) cells (Chopra and Das, 1983). The thin-film solar cells employ a heterojunction between two metal sulfides, one of which is  $\text{Cu}_2\text{S}$  (p-junction) and the other a sulfide of Cd or  $\text{ZnCd}$  (n-junction). Such cells are still being perfected;

efficiencies were around 7% in the mid-1970s but had risen to about 10% by 1981. One advantage of these cells is that they are, as the name implies, thin films of relatively light mass. The cells are layered structures, with layers as thin as a few tens or hundreds of angstroms deposited in sequence. Total thickness of the cell would typically be 5 to 50  $\mu\text{m}$ . The efficiency of present  $\text{Cu}_2\text{S}/\text{CdS}$  cells crests at light intensities between 20 and 120  $\text{mW}/\text{cm}^2$ , a range that includes the one-sun intensity of 50  $\text{mW}/\text{cm}^2$ . Although the efficiency of this system is currently less than half that of some advanced photovoltaics systems now under investigation (InP or GaAs; Flood, 1986), there is a possible advantage in that the sulfur would not have to be imported.

In practice, the need for some material imports (mostly Cd) may be a potential problem in production of thin-film solar cells on the Moon. Most of the cell mass is Zn and Cd, and Cd is critical to efficient thin-film cells. Although there is good reason to believe that both S and Zn are concentrated in lunar pyroclastic deposits (0.02% Zn, Butler and Meyer, 1976), Cd is not comparably enriched. In addition, once the cells are produced, it is not known how well they might survive in the space environment. Still, this is an energy conversion system that is worth serious consideration. One potentially advantageous aspect of the thin film cells is the evidence that vacuum evaporation is probably the best method for cell production (Chopra and Das, 1983). This is one production system that might make good use of the free vacuum in space.

An alternative approach to the use of sulfur in solar energy collection is through a photoelectrochemical (PEC) effect. Sulfur is important in the electrolyte solution as a "hole scavenger" at the photoanode. A well studied PEC cell configuration uses a CdSe photoanode with a CdS interface against an electrolyte (Chopra and Das, 1983). One practical electrolyte contains various proportions of  $\text{Na}_2\text{S}$ , S, and NaOH (Russak et al., 1980). The cell efficiencies observed range from 3% to 8%. As with the thin film cells, a potential drawback may be the need to import Cd and, in this case, Se for lunar production. Economic study may well show that it would be more advantageous to form light photocells on Earth and export them intact to the



Moon, or to rely on possible crude but rugged cells such as those that might be made out of minimally processed lunar ilmenite (Meek et al., 1987).

#### Electrical Energy Storage

The greatest payoff in the use of indigenous lunar sulfur for electrical applications may be in the in-situ production of relatively massive storage batteries. Sulfur-based storage batteries have widespread applications on Earth. In addition to the ubiquitous  $\text{Pb-PbO}_2\text{-H}_2\text{SO}_4$  battery (which, unfortunately for lunar use, requires precious water), there is active research in the development of molten electrolyte Na-S storage cells for electric vehicles. These cells operate at about  $300\text{-}350^\circ\text{C}$ , with a two-stage discharge that derives electrons from Na-to- $\text{Na}^+$  oxidation by (1)  $5\text{S} + 2\text{Na} \rightarrow \text{Na}_2\text{S}_5$  and (2)  $3\text{Na}_2\text{S}_5 + 4\text{Na} \rightarrow 5\text{Na}_2\text{S}_3$ . The discharge voltage of the cell varies with the reaction stage, from about 2.08 V for reaction (1) to 1.76 V for reaction (2) (Bagatzky and Skundin, 1980). The predicted cell performance for the near future is 150-200 W-hr/kg. A schematic cross section of a Na-S storage battery is shown in Figure 2.

The electrolyte for the cell is a sodium polyaluminate ( $\text{Na}_2\text{O} \cdot n\text{Al}_2\text{O}_3$ , with  $n = 3\text{-}11$ ) that is porous to  $\text{Na}^+$ . This electrolyte is formed as a ceramic and is difficult to manufacture (Bagatzky and Skundin, 1980); this component and the porous graphite positive electrode would probably have to be supplied from Earth. The requirement for Na as well as S may be viewed critically in terms of availability on the Moon, but there is some evidence for Na associated with the surface-deposited volatiles of lunar pyroclastic deposits (Cirlin and Housley, 1979). The sodium mineralogy and abundances in these deposits are poorly known, but the possible use in batteries justifies further study. Should the indigenous lunar sulfur be found insufficient, a useful alternative may be to import NaOH which could be processed after arrival to provide Na,  $\text{O}_2$ , and  $\text{H}_2\text{O}$  (all of great value on the Moon).

#### The Use of Sulfur Chemical and Biochemical Properties

The chemical uses of sulfur are so varied that we can only touch on a few in this paper. The examples chosen are those that appear to the authors to have important potential applications on the Moon.

### Sulfuric Acid

Sulfuric acid usage is a common measure of industrial capacity on Earth; this acid has so many uses that it is practically a generic guide to productivity. A large number of potential uses on the Moon might be considered, but these must be weighed against the need to consume water in the production of sulfuric acid. As one example of possible uses, the acid could dissolve surface-deposited volatiles and agglutinate glasses from the surfaces of metallic iron fragments separated magnetically from lunar soil (Haskin, 1985). Since the agglutinates themselves have some magnetism due to fine-scale entrapped iron, an acid bath of crushed and soil might be sufficient to separate metal from glass through Stokes' law settling while the iron is being stripped of glass attachments. A very different example of sulfuric-acid use would be the destruction of organic waste as part of a Closed Ecological Life Support System ("CELSS"; MacElroy et al., 1985). Highly concentrated sulfuric acid can remove hydrogen and oxygen from some organic compounds to produce water; simple plant sugars might be processed in this manner.

The production of sulfuric acid on the Moon might occur as a variant of the terrestrial contact process, in which  $\text{SO}_3$  is made by catalytic oxidation of  $\text{SO}_2$  (over platinum or vanadium pentoxide) and bubbled through relatively dilute sulfuric acid to produce concentrated acid. This process would require oxygen input to oxidize the relatively reduced sulfur that occurs in lunar regolith. Sulfuric acid can also be produced by electrolysis of  $\text{SO}_2$  in water (see section on thermochemical water-splitting, below). In a closed system, the depletion of water and oxygen could be minimized but some loss will probably be incurred and the benefits must be weighed against this loss.

### Sulfur Sealants

Lunar habitats must be capable of maintaining a pressurized atmosphere. Some redundancy in sealants to contain the atmosphere is desirable, and a method of spray-impregnating walls of regolith or the internal surfaces of lava tubes might be useful. Thioelastomers (Thiokols) can be mixed with small amounts of molten sulfur to make extremely tough materials (Leclercq.

1972). The production requirements of hard or rubbery coatings are presently too complex for simple extension to the Moon, but imaginative use of organic waste with lunar sulfur might produce a useful sealant.

#### Thermochemical Water-Splitting

Water can be split into  $H_2$  and  $O_2$  for collection and cooling to provide liquid rocket propellant. On a smaller scale, water might be split for use in hydrogen fuel cells. Fuel cells may be particularly useful if the water is reclaimed at the exhaust. There are several options for producing  $H_2$  from water on the Moon; extraction from waste methane and electrolysis of water are both possible. Thermochemical splitting of water, however, would be advantageous where reactor power is available to provide a high-temperature heat source. Dokiya et al. (1979) describe both an  $SO_2$  hybrid cycle and a  $SO_2$ - $H_2S$  cycle for thermochemical splitting of water. The  $SO_2$  hybrid cycle uses electrolysis of  $SO_2 + 2H_2O$  to produce  $H_2SO_4 + H_2$ , followed by thermal dissociation of the sulfuric acid at 800-850°C to produce  $H_2O + SO_2 + 1/2O_2$ . The  $SO_2$ - $H_2S$  cycle requires only heat energy (830°C), but has four steps and requires input of both  $H_2S$  and  $SO_2$  as well as water. For lunar applications the  $SO_2$  hybrid cycle is probably most attractive because of its relative simplicity (two steps instead of one) and the relative conservation of sulfur as  $SO_2$  (output ideally equals input, but is limited by 70-80% conversion efficiency). The most significant drawback of this method is the requirement for use of electrical as well as thermal energy.

#### Sulfur as a Fluxing Agent

Sulfur is used terrestrially as a fluxing agent, in reducing the melting points of glasses. This use may also be practical on the Moon, where glass production may be sought for structural uses (Blacic, 1985). Experiments with a variety of regolith-sulfur mixtures are needed to determine the utility of such a process.

#### The Brimstone Rocket

Production of rocket propellants from lunar resources would be a major boon for expanded space exploration (National Commission on Space, 1986). There has been considerable study of systems to produce oxygen from lunar regolith, particularly from concentrates of lunar ilmenite (Cutler and Krag,

1985; Gibson and Knudsen, 1985). Lunar sources of fuels to be oxidized, however, are extremely scarce. Hydrogen is so rare that any use for propellant would almost certainly require expensive imports, perhaps as methane or ammonia from Earth (Friedlander, 1985). Other fuels such as silane ( $\text{SiH}_4$ ; Rosenberg, 1985) might be produced in part from lunar feedstocks, but would still require hydrogen imports. In contrast, sulfur might provide a truly indigenous lunar fuel.

Some sulfur release will be an inevitable byproduct of lunar oxygen production. Lunar oxygen production is targeted on mare regoliths with high ilmenite content; these are also the regoliths with highest sulfur content (0.06 to 0.13%; see Table 1). In an oxygen production plant such as Cutler and Krag (1985) envision, the sulfur byproduct would be about 1% of the  $\text{O}_2$  mass produced, assuming 0.1% collectable S in the ilmenite-enriched feedstock. If the tailings from ilmenite enrichment are also processed for sulfur removal, then total sulfur production would be about 10% of the  $\text{O}_2$  mass. These proportions permit serious consideration of a S- $\text{O}_2$  propulsion system (a "brimstone" rocket).

The brimstone rocket could be fueled with liquid sulfur and liquid oxygen, the sulfur being kept between 150-160°C where its viscosity is lowest and it is easiest to pump. Atomized droplets of liquid sulfur would be introduced with gaseous oxygen into the combustion chamber. Here the exothermic reaction to  $\text{SO}_2$  would liberate 4598 kJ/kg  $\text{SO}_2$  at a temperature near 2200°C. Isotropic expansion into the vacuum of the lunar environment would result in an ideal exhaust velocity of 2916 m/sec, giving a specific impulse ( $I_{sp}$ ) of 298 seconds. Real nozzles operate at about 90% of the ideal specific impulse.

The specific impulse of the brimstone rocket would be useful for pogo-sticking from one point to another on the lunar surface, for putting payloads into lunar orbit, or for more ambitious missions beyond the Moon. Using electrostatic mass ejection systems on the lunar surface, large amounts of sulfur fuel and oxygen could be gradually accumulated at Lagrange launch points for deep-space exploration missions. Such remote low-gravity fueling depots are attractive, but the advantages of such a system should be

weighed against the high ratio of payload to fuel mass that can be obtained in launches directly from the lunar surface. To place a payload into a 100 km lunar orbit requires that the initial rocket mass at launch be 48% propellant. This low propellant mass stems from the low lunar gravitational acceleration and the respectable specific impulse of the brimstone rocket. A brimstone rocket leaving the Moon would have considerable room for payload and structural mass.

The exhaust gasses from the brimstone rocket would be compatible with the lunar environment. Sulfur dioxide is a condensable gas, which would ultimately be deposited as coatings on the regolith if released into the lunar environment. This condensation mechanism will prevent a significant lunar atmosphere from developing to hinder scientific operations at a lunar base. A large fraction of the sulfur fuel will also stay within the lunar environment. The impact of even a large-scale launch operation will be mitigated because most of the brimstone rocket exhaust will stay on the Moon.

In contrast, rockets based on reduced metals and excess oxygen (e.g., Mg-O<sub>2</sub>) will liberate large quantities of oxygen into the lunar environment. This oxygen could build up to a significant atmosphere and, worse yet, provide oxidizing conditions which would alter the pristine reduced state of the lunar regolith.

#### Sulfur for Plants, Animals and People

Sulfur is a necessary trace element in the diets of many organisms, including people. Powdered sulfur also has uses in plant fertilization (Leclercq, 1972). These uses could probably be met simply by the use of unprocessed lunar soil in CELSS systems. For radiation protection, however, it is worth considering the inclusion of small-scale pharmaceutical production of sulphydryl compounds in space for advanced CELSS systems.

Because nitrogen and other inert gasses will be scarce on the Moon, it is likely that the atmospheres in lunar habitats will be oxygen-rich. One consequence of this may be a long-term increase in susceptibility to sickness and biological damage from ionizing radiation (von Sonntag, 1987). Sulphydryl compounds are the most extensively studied and effective means of

chemical prophylaxis against radiation damage (von Sonntag, 1987; IAEA, 1969). The action of these compounds is still incompletely understood, but there is considerable evidence that one of their effects is not entirely unlike the role of sulfur in photocells, where the ability of sulfur to assume a large variety of electron shell configurations will not abide an association with electron holes or active charged radicals (see section on PEC photocells, above). Energy transfer from ionizing radiation into biological materials produces target radicals, which will produce cellular damage if left "unquenched". Potentially damaging hydrogen ionization induced in a biological target can release a proton, leaving a target radical with chemical activity that may eventually result in permanent damage. The sulphydryl compounds can split rapidly to donate a replacement hydrogen before permanent damage occurs (von Sonntag, 1987).

The amount of sulfur in sulphydryl compounds is actually quite small. Glutathione, a well-studied example, has only one sulfur in a molecule of 37 atoms (the rest being H, O, N, and C). These compounds are not heavy users of sulfur resources, and for the near future are probably best produced on Earth even if a use is found for them in space. On the other hand, a flurry of early research into new sulphydryl compounds has now stagnated (von Sonntag, 1987) but might be renewed if considered in terms of the space environment. The advances made in synthesizing pharmaceuticals under microgravity conditions may be applicable to advances in chemical protection from ionizing radiation. Ultimately, the use of lunar sulfur may play a role in expanded human occupation of near-Earth space.

### Conclusions

It is fortuitous to find a relatively abundant supply of sulfur on the Moon. Although elemental sulfur has not been proven to occur, even the  $\text{SO}_2$  that may be released from metal sulfates could provide sulfur fuel as a byproduct of oxygen production for a variety of uses. In an environment devoid of gas-forming elements, sulfur has the potential to provide as significant an impact on lunar development as coal and petroleum had for the industrialization of society on Earth.

Even at its low abundance in lunar regolith, the ~0.1% of sulfur available across many thousands of square kilometers of high-Ti mare regolith may be useful. Thermal processing of mildly crushed regolith from high-Ti basaltic lava areas at 1100°C could yield about one metric ton of sulfur from a patch of regolith 100 m x 100 m and 10 cm deep. Figure 3 shows the possible scars that would be left by much more extensive mining in two types of regolith at the Apollo 17 site. Each scar has an area of about 10 km<sup>2</sup>, but patch A would produce ~1000 metric tons of sulfur from high-Ti basaltic lava regolith whereas patch B would produce ~700 metric tons of sulfur with co-generation of the metals and sodium that occur on the surfaces of pyroclastic glasses. Either patch would produce sufficient sulfur to lift a payload of several hundred metric tons off of the Moon using the brimstone rocket.

In practice these patches would not be nearly so regular or well contained; patch A in particular would have to be gerrymandered to avoid large craters in the basaltic lava regolith (the pyroclastic mantle is much smoother, and crater avoidance would be less of a problem in patch B). It is possible that these mined areas would not leave visible scars. The most efficient extraction system could be a mobile processing plant which would return more than 99% of the processed regolith and leave no trench. Such a system would be merely one more gardening event at the lunar surface. The depth of excavation would be strongly process dependent (considering plant mobility versus plant simplicity); shallow excavation simplifies the mining equipment at the cost of making the plant more mobile.

If dedicated solely to sulfur and associated volatile-element production, the thermal energy required for this plant would be about 0.1 Mw-yr per metric ton of sulfur (assuming 100% duty cycle). Significant energy savings might be realized if sulfur production were piggybacked with oxygen production, or if low-energy solvent extraction of sulfur were developed to replace thermal extraction. Clearly, process development with a clear definition of end use is necessary if lunar sulfur is to be taken seriously as a potential resource. The beginnings of this process must be a better understanding of the mineralogy and parageneses of sulfur and its co-deposited elements at the lunar surface.

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#### references

- Bagotzky V.S. and A.M. Skundin (1980) Cells with solid and molten electrolytes. In Chemical Power Sources, Academic Press, NY, 320-337.
- Blacic J.D. (1985) Mechanical properties of lunar materials under anhydrous, hard vacuum conditions: Applications of lunar glass structural components. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 487-495.
- Burow D.F. (1970) Liquid Sulfur Dioxide. In The Chemistry of Nonaqueous Solvents, Vol. III (J.J. Lagowski, ed.), Academic Press, New York, pp. 137-185.
- Butler P. Jr. and Meyer C. Jr. (1976) Sulfur prevails in coatings on glass droplets: Apollo 15 green and brown glasses and Apollo 17 orange and black (devitrified) glasses. Proc. Lunar Sci. Conf. 7th, pp. 1561-1581.
- Chopra K.L. and S.R. Das (1983) Thin Film Solar Cells. Plenum Press, New York, pp. 349-389 and 391-481.
- Cirlin E.H. and Housley R.M. (1979) Scanning auger microprobe and atomic absorption studies of lunar volcanic volatiles. Proc. Lunar and Plan. Sci. Conf. 10th, pp. 341-354.
- Cutler A.H. and P. Krag (1985) A carbothermal scheme for lunar oxygen production. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 559-569.
- Dokiya M., K. Fukuda, T. Kameyama, and H. Yokokawa (1979) A feasibility study on thermochemical water-splitting cycles using sulfur compounds. In Hydrogen Energy System, Vol. 2, Proc. 2nd World Hydrogen Energy Conf., Pergamon Press, NY, 499-512.



- Flood D.J. (1986) Space solar cell research: Problems and potential. In SPIE Vol. 706, Photovoltaics for Commercial Solar Power Applications (D. Adler, ed.), Proceedings of SPIE - The Int. Soc. for Optical Engineering, SPIE, Bellingham, WA, 34-39.
- Friedlander H.N. (1985) An analysis of alternate hydrogen sources for lunar manufacture. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 611-618.
- Gibson, E.K. Jr., Brett R., and Andrawes F. (1977) Sulfur in lunar basalts as a function of bulk composition. Proc. Lunar Sci. Conf. 8th, pp. 1417-1428.
- Gibson E.K. Jr. and Moore G.W. (1973) Carbon and sulfur distributions and abundances in lunar fines. Proc. Lunar Sci. Conf. 4th, pp. 1577-1586.
- Gibson E.K. Jr. and Moore G.W. (1974) Sulfur abundances and distributions in the valley of Taurus-Littrow. Proc. Lunar Sci. Conf. 5th, pp. 1823-1837.
- Gibson M.A. and C.W. Knudsen (1985) Lunar oxygen production from ilmenite. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 543-550.
- Haskin L.A. (1985) Toward a Spartan scenario for use of lunar materials. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.) The Lunar and Planetary Institute, Houston, 435-443.
- IAEA (International Atomic Energy Association) (1969) Radiation Damage and Sulphydryl Compounds, Panel Proceedings Series, Int. Atomic Energy Ass., Vienna, 191 pp.
- Kerridge J.F., Kaplan I.R., and Petrowski C. (1975) Evidence for meteoritic sulfur in the lunar regolith. Proc. Lunar Sci. Conf. 6th, pp. 2151-2162.
- Leclercq R. (1972) Commercially important sulfur compounds. In Sulfur in Organic and Inorganic Chemistry (A. Senning, ed.), Marcel Dekker Inc., New York, 207-221.
- LSPET (Lunar Sample Preliminary Examination Team) (1972) Preliminary examination of lunar samples. In Apollo 16 Preliminary Science Report, NASA SP-315, Washington, D.C., pp. 7-1 to 7-58.
- MacElroy R.D., H.P. Klein, and M.M. Averner (1985) The evolution of CELSS for lunar bases. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 623-633.

- Meek T.T., D.T. Vaniman, R.D. Blake, and F.H. Cocks (1987) Electromagnetic energy applied to and gained from lunar materials. In Symposium '86: The First Lunar Development Symposium (G.M. Andrus, Ed.), Lunar Development Council, Pitman, NJ, S86-40a to S86-40e.
- Meyer C. Jr., D.S. McKay, D.H. Anderson, and P. Butler, Jr. (1975) The source of sublimates on the Apollo 15 green and Apollo 17 orange glass samples. Proc. Lunar Sci. conf. 6th, pp. 1673-1699.
- Muehlberger W.R., R.M. Batson, E.A. Cernan, V.L. Freeman, M.H. Hait, H.E. Holt, K.A. Howard, E.D. Jackson, K.B. Larson, V.S. Reed, J.J. Rennilson, H.H. Schmitt, D.H. Scott, R.L. Sutton, D. Stuart-Alexander, G.A. Swann, N.J. Trask, G.E. Ulrich, H.G. Wilshire, and E.W. Wolfe (1973) Preliminary geologic investigation of the Apollo 17 landing site. In Apollo 17 Preliminary Science Report, NASA SP-330, Washington, D.C., pp. 6-1 to 6-91.
- National Commission on Space (1986) Pioneering the Space Frontier. Bantam Books, NY, 211 pp.
- Rosenberg S.D. (1985) A lunar-based propulsion system. In Lunar Bases and Space Activities of the 21st Century (W.W. Mendell, ed.), The Lunar and Planetary Institute, Houston, 169-176.
- Russak M.A., J. Reichman, H. Witzke, S.K. Deb, and S.N. Chen (1980) Thin film CdSe photoanodes for electrochemical photovoltaic cells. Jour. Electrochem. Soc. 127, 725-733.
- von Sonntag C. (1987) The Chemical Basis of Radiation Biology. Taylor and Francis, NY, 515 pp.
- Weast R.C. (ed.) (1982) Handbook of Chemistry and Physics, 63rd edition, CRC Press, Boca Raton, FA, F-46.
- Williams R.J. and J.J. Jadwick (eds.) (1980) Handbook of Lunar Materials. NASA Reference Pub. 1057, 120 pp.

## figure captions

Figure 1. Viscosity of liquid sulfur (gas free) as a function of temperature (data from Weast, 1982).

Figure 2. A molten electrolyte Na-S battery (after Bagotzky and Skundin, 1980).

Figure 3. A simplified version of an albedo map of the Apollo 17 landing site (modified from Muehlberger et al., 1973). Massifs and hills of the non-basaltic highlands surround an embayment flooded by high-titanium, high-sulfur basalts (light pattern); the eastern part of the embayment includes a terrain of very low albedo (dark pattern) which is attributed by Muehlberger et al. to an extensive pyroclastic mantle. Squares A and B show the dimensions of 10 km<sup>2</sup> x 10 cm deep patches mined out of the regolith; A would yield ~10<sup>3</sup> MT of sulfur and B would yield ~7x10<sup>2</sup> MT.

## FLUID PROPERTIES OF SULFUR

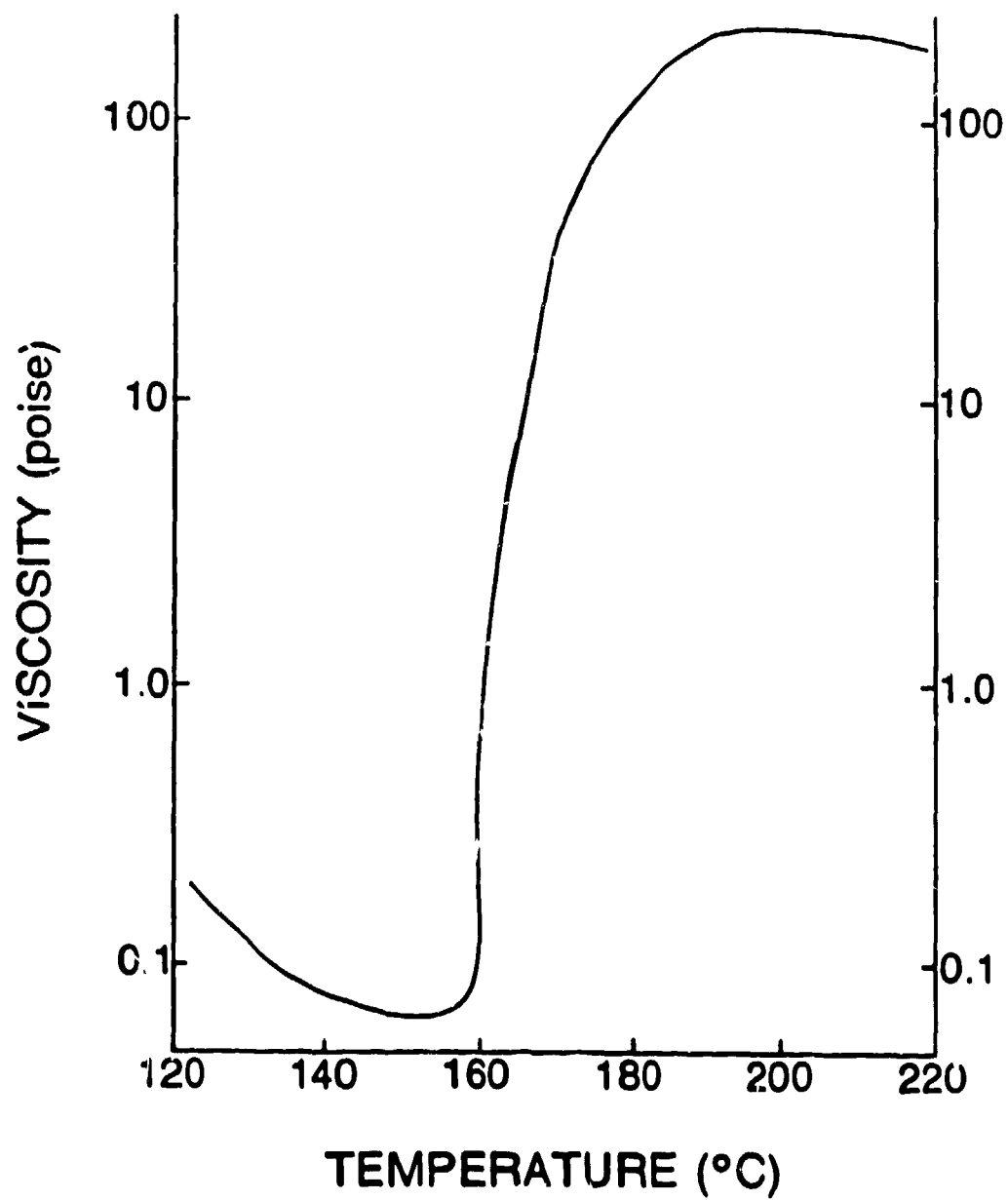


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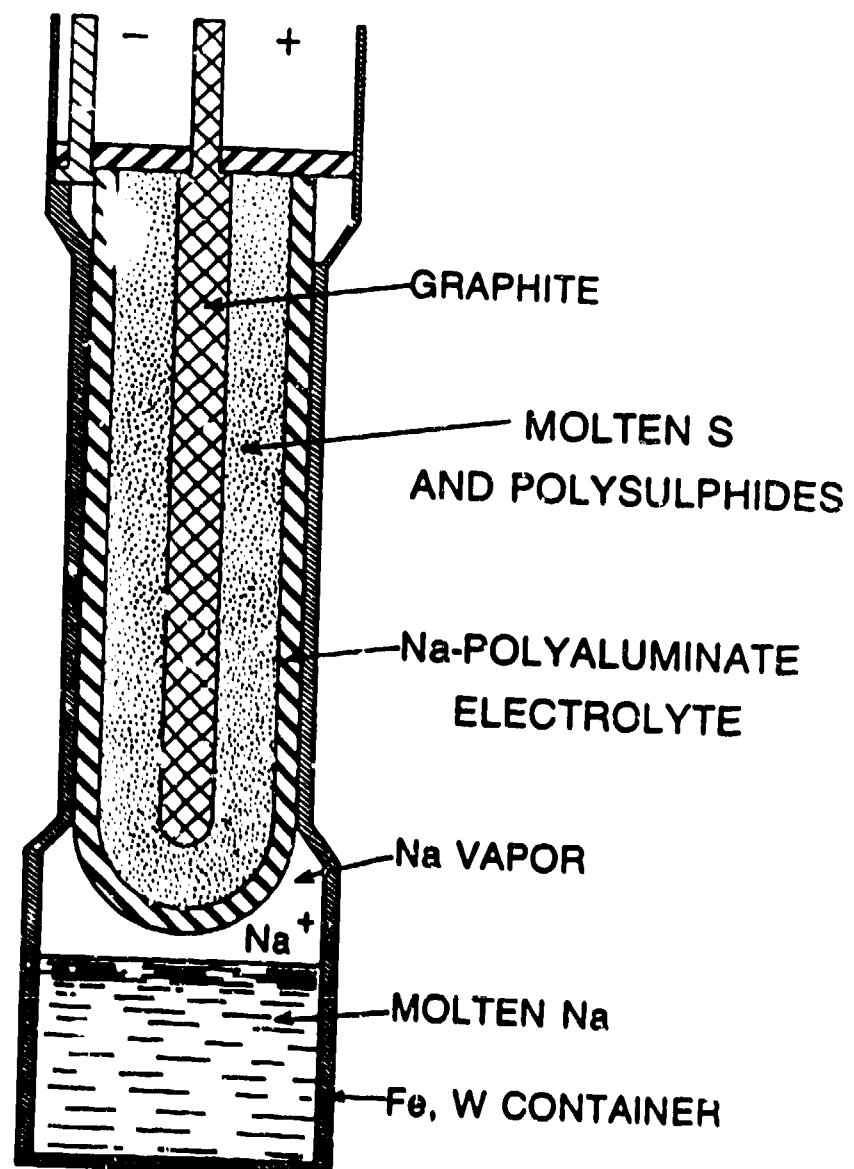


Figure 2. A molten electrolyte Na-S battery (after Bagotsky and Skundin, 1980).

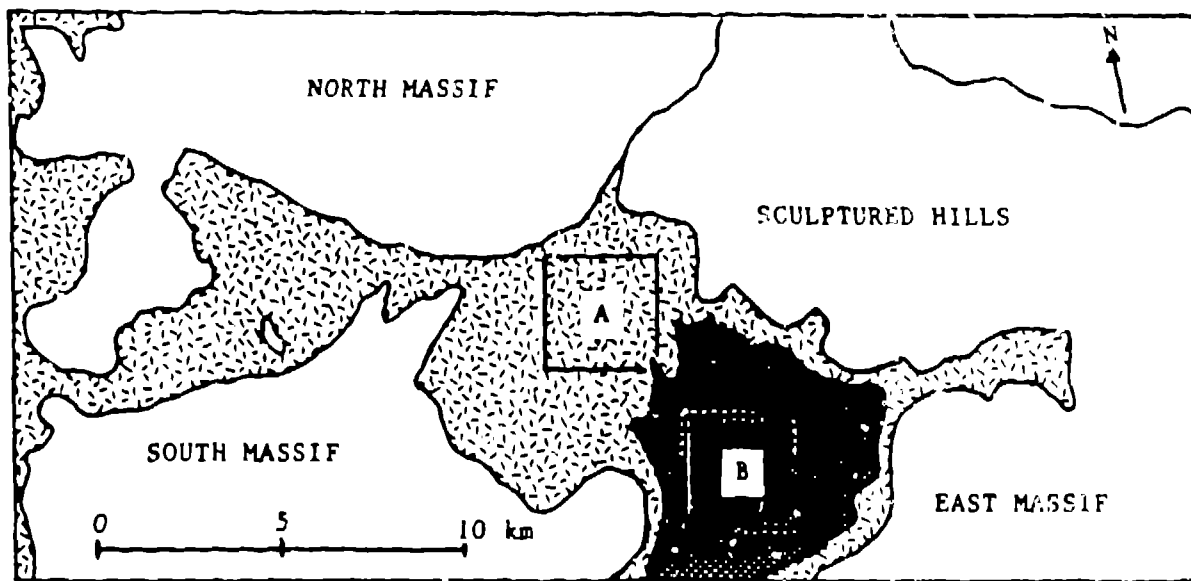


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